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Federal Aviation Administration

Impact of Weight Changes on Aircraft Fuel Consumption

DRAFT REPORT

July 20, 1998

HICKLING LEWIS BROD INC.

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IMPACT OF WEIGHT CHANGES ON AIRCRAFT FUEL CONSUMPTION

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July 20, 1998
HLB Reference: 6514
File Name: FuelB .doc

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1. INTRODUCTION

This report is an update of the 1994 report on the impact of weight changes on aircraft fuel consumption. As in the 1994 report, this update presents look-up tables of incremental aircraft fuel consumption caused by small increases in aircraft weight. The look-up tables provide the basis for the Federal Aviation Administration (FAA) to determine the fuel consumption impacts associated with regulatory changes that affect the operating weight of aircraft. The representative airplanes selected for the look-up tables are all Stage 3 aircraft in compliance with the Airport Noise and Capacity Act of 1990 (ANCA). This act requires a phased elimination of the operation of civil, subsonic Stage 2 turbojet airplanes over 75,000 pounds to or from airports in the contiguous United States by December 31, 1999.

Another feature in this report is that it categorizes aircraft by (?) ~~per~~ user category (scheduled commercial services: air carrier without commuters and commuter only; and general aviation and air taxi), FAR category (25, 23, 27, and 29), and operation category (based on the number of engines and seats).

The fuel consumption impacts reported are based on industry accepted flight planning models and manufacturer's specifications. Details of the flight planning models and how they were employed in the generating of the impacts are also presented in this report. The listed aircraft exhibit a minimum of 50% frequency of use (airborne hours) for each operational category.

Adopting flight planning models to meet FAA requirements required identifying aircraft categories that correspond to FAA regulations and determining representative aircraft within each category. Section 2 defines the aircraft categories and corresponding representative aircraft that are displayed in the look-up tables. Section 3 presents the incremental fuel consumption estimates and the approach used to develop the results. The final section discusses the time table for the review and update of the incremental fuel consumption estimates.

2. METHODOLOGY IN DEFINING REPRESENTATIVE AIRCRAFT

2.1 Background

This update from 1994 report is largely guided by the choice of new representative aircraft. These aircraft change over time with the change in the composition of the fleet. The significant technological and regulatory trends governing the aircraft fleet concern noise reduction.

Dealing with aviation noise has become an important factor for the federal government. Until recently, the main aviation noise emphasis has been on the big jet airplanes. This emphasis began in the early 1960's with the rapid expansion of turbojet aircraft into the civil aviation market. It led to the first noise certification standards in 1969, establishing Stage 2 standards for new types of large commercial airplanes. This was followed successively by setting Stage 3 standards in 1977 and the phaseout of Stage 1 airplanes in 1985. The FAA now is engaged in phasing out the large Stage 2 airplanes by the turn of the century.

This section describes the rationale for selecting representative Stage 3 aircraft for 15 operational categories of aircraft that fall under Federal Aviation Regulations 23, 25, 27 and 29 (Table 2.1). The determination of the representative aircraft in each category was based on the following criteria:

- Frequency of Use
- Average Takeoff Weight
- Fuel Consumption

Potential representative aircraft were identified by comparing airborne hours in the aircraft category. Frequency of use was determined by computing the percentage of airborne hours for each aircraft in the category. All representative aircraft exhibited a minimum of 50% frequency of use. Potential representative aircraft were then compared on the basis of average takeoff weight and fuel consumption.

Table 2-1: Classification of Categories of Aircraft for Fuel Consumption Estimation

User Category	FAR Category	Aircraft Operational Category
Scheduled Commercial Services Air Carrier without commuters Commuter Only	1. Transport FAR 25	a) Jet: 4 engine wide body b) Jet: 4 engine narrow body c) Jet: 3 engine wide body d) Jet: 3 engine narrow body e) Jet: 2 engine wide body f) Jet: 2 engine narrow body g) Jet: Regional under 40 seats h) Jet: Regional with 40-59 seats i) Jet: Regional over 59 seats
General Aviation and Air Taxi	2. Commuter, Normal, Utility Acrobatic FAR 23	a) Turbo Prop (20 or more b) Turbo Prop (under 20 c) Multi-Engine d) Single Engine
	3. Normal FAR 27	Rotorcraft (<6,000 lbs) Turbine
	4. Transport FAR 29	Rotorcraft (>6,000 lbs) Turbine

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The remainder of this section provides the selection tables that were used to determine representative aircraft. Selected aircraft are representative in terms of average takeoff weight, fuel consumption, and frequency of use. The tables highlight the representative aircraft that are contained in the look-up tables in Section 3.

2.2 Scheduled Commercial Services-FAR 25 Aircraft

FAR 25 regulations relate to transport category airplanes listed under Scheduled Commercial Services. For the purposes of this report, they are categorized by the number of engines (2, 3, or -4), the type of body (wide or narrow), the number of seats for regional jets, and common use (private or commercial).

Tables 2.2 through 2.10 display aircraft categories that were considered. The tables list the aircraft type, 1996 airborne hours, airborne speed, average takeoff weight, and fuel burn in gallons per hour. The representative aircraft in all categories exhibit high frequency of use, typical fuel burn performance and average takeoff weight.

Table 2-2: Characteristics of 4 Engine Wide Body Jets Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
747-100	203,531	520	750,005	3,638
747-200/300	52,226	525	786,000	3,663
747-400	167,329	538	875,000	3,410

Table 2-3: Characteristics of 4 Engine Narrow Body Jets Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
BAE-146-2	9,131	288	90,375	N/A
BAE-146-3	29,649	335	97,250	N/A
DC-8-62	14,799	474	344,300	2,114
DC-8-63	1,390	526	350,300	2,283

Table 2-4: Characteristics of 3 Engine Wide Body Jets Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
DC-10-1	173,020	500	438,500	2,287
DC-10-3	153,489	520	568,625	2,667
L-1011	180,958	492	430,000	2,428
L-1011-5	74,061	522	501,500	3,829
MD-11	135,991	524	612,714	2,462

Table 2-5: Characteristics of 3 Engine Narrow Body Jets Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
727-100	772	439	174,500	1,284
727-200	1,213,062	437	203,100	1,287

Table 2-6: Characteristics of 2 Engine Wide Body Jets Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
A300-600	92,943	460	355,000	1,678
B-767-2/ER	333,977	485	360,500	1,409
B-767-3/ER	480,968	494	369,000	1,602
B-777	53,597	511	548,000	2,117

Table 2-7: Characteristics of 2 Engine Narrow Body Jets Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
A320-1/2	383,236	456	156,000	820
B737-1/2	775,127	386	124,500	824
B737-3	1,570,316	414	131,000	776
B737-4	261,865	413	142,500	792
B737-5	372,952	412	132,800	747
B757	1,341,922	463	235,000	1,050
DC-9-10	77,990	378	90,700	743
DC-9-30	642,432	389	107,000	810
DC-9-50	142,913	375	118,000	915
MD-80	1,900,678	431	149,500	933

Table 2-8: Characteristics of Regional Jet under 40 Seats Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
LEAR-24	N/A	79.2	13,500	125
LEAR-25	N/A	161.0	15,000	125
LEAR-35	N/A	50.2	17,500	125

Table 2-9: Characteristics of Regional Jet with 40-59 Seats Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
CL600	N/A	158	40,400	812
CL601	171,070	158	43,100	812

Table 2-10: Characteristics of Regional Jet with 40-59 Seats Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
F-100	N/A	383	98,000	646

2.3 General Aviation and Air Taxi

2.3.1 FAR 23 Aircraft

FAR 23 regulations relate to commuter, normal, utility and acrobatic airplanes. For the purposes of this report, they are categorized by the type of engine (piston or turboprop); the number of engines (single or multiple) and the number of seats (under or over 20 seats).

Tables 2.11 through 2.14 present the aircraft that were considered. The tables list for each aircraft type, airborne hours, airborne speed, the average takeoff weight, and total fuel burn. The representative aircraft exhibit high frequency of use, typical fuel burn performance and average takeoff weight.

Table 2-11: Characteristics of Turbo Props 20 or more Seats Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
SHORT-360	1,832	158	25,750	N/A
SF-340	N/A	195	28,000	121
DASH-8	3,740	218	33,000	167
EMB-120	N/A	180	25,353	160

Table 2-12: Characteristics of Turbo Props under 20 Seats Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
BEECH 100	N/A	150	11,800	59
DASH 6	10,439	168	11,000	55
KING AIR B200	N/A	168	12,500	48
METRO-III	11,544	245	14,500	72

Table 2-13: Characteristics of Multi Engine Pistons Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
DC-6	N/A	213	6,800	27
BEECH E55	N/A	185	5,200	25
PIPER 31	43,233	168	6,000	21
CESSNA 310	N/A	166	5,000	27

Table 2-14: Characteristics of Small Engine Pistons Considered

Aircraft Type	Airborne Hours	Speed Airborne	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons per Hour
CESSNA 172	4.297	145	2,650	12
CESSNA 182R	N/A	153	2,850	11
PIPER 32	32,824	160	3,600	13

2.3.2 FAR 27 and FAR 29 Rotorcraft

While there a large number of rotorcraft types that fall into the two categories defined by FAR parts 27 and 29, the representative aircraft were selected based in part on those for which reasonable fuel burn information was available. These two categories are listed under the General Aviation and Air Taxi user category. Research was conducted with the assistance of an aircraft experts from Navtech Systems in Canada, to select two rotorcraft within the regulatory categories.

The selection of these aircraft considered availability of flight planning data, as well as the criteria listed earlier in this section (i.e., airborne hours and speed, average takeoff weight, frequency of use and fuel consumption). The following two aircraft were selected based on this criteria:

3. FUEL CONSUMPTION ESTIMATES: ANALYSIS AND SOURCES USED

This section presents the estimates of incremental fuel consumption for each of the 15 aircraft categories in the form of a look-up table. The flight planning model, data sources and assumptions used in developing these estimates are also described in this section.

3.1 Analysis of the Fuel Consumption Estimates

The Incremental Fuel Consumption Look-up Table (Table 3.2) is composed of three sections: FAR 25 Aircraft, FAR 23 Aircraft and FAR 27 and 29 Rotorcraft. The estimates are presented in gallons per airborne hour per pound increase.

For each aircraft two input values were required: Maximum Takeoff Weight, and Average flight time in minutes. For TOW, the analysis used the Maximum Gross Takeoff Weight listed in the FAA's list of Stage III compliant turbojet aircraft, with three exceptions: the DC10, B737, and CL600 (RJ). With these aircraft the limiting factor for the average flight times being used becomes the Maximum Landing Weight. In other words, if you were to depart at MTOW and fly for the specified time, you would not have burned sufficient fuel to be below the Maximum Structural Landing Weight of the aircraft. For these three aircraft, the analysis used a baseline TOW that would result in the aircraft arriving at destination at the max. landing weight shown in the FAA listing.

Analysis of FAR 25 aircraft estimates indicates that the relationship between the weight increment and additional fuel consumed is close to being linear (i.e., the fuel penalty per pound weight increase does not vary significantly with the increment of weight). Typical weight penalties may range from under 50 pounds up to 500 pounds, and thus the table provides fuel consumption estimates for weight increases categories within this range.

FAR 23, 27 and 29 aircraft exhibit linear relationships between weight increments and the additional fuel consumed. Increasing weight by 10, 20 or 100 pounds has the same affect on the additional gallons of fuel consumed per airborne hour per pound increase. As a result, the tables show the same estimate of incremental fuel burn for all aircraft operating weight increases up to 100 pounds. Table 3.1 below explains how to use the look-up table.

Table 2-15: Characteristics of FAR 27 and FAR 29 Rotorcraft Considered

Rotorcraft Type	Average Takeoff Weight in Pounds	Total Fuel Burn in Gallons Per Hour
FAR 27: MBB 125	3500	25
FAR 29: B212	7500	45

Table 3-1: Example of Look-up Table Use

FAR 25 Category: Jet: 3 Engine narrow **Representative Aircraft:** B727 - 200 **Average en Route Time**: 180 minutes			
Weight Increment	**Coefficients (Table 3-2)**	**Calculation**	**Fuel Burn Estimate (Gallons per airborne hour)**
Weight Increment 1: 30 Pounds	0.010079	0.010079 * 30	0.30237
Weight Increment 2: 62 Pounds	0.010088	0.010088 * 62	0.625456
Weight Increment 3: 250 Pounds	0.010089	0.010089 * 250	2.52225

3.2 Description of Flight Planning Model and Data Sources

This report adapted an industry accepted flight planning model to determine the incremental fuel consumption for the four categories of aircraft.[1] The flight planning model predicts en route fuel burn using a formula that is specific to the following variables; aircraft type, series and engine combinations and flight path. Coefficients in the formula are determined by a program that runs several hundred flight plans for each set of variables and performs regression curve fitting techniques on the results.

The model uses climb, cruise, descent, and holding performance data obtained from operator flight manuals or from data provided by manufacturers. These data are loaded into the flight planning model which calculates fuel consumption assuming International Standard Atmospheric (ISA) conditions.

[1] The flight planning model was developed by Navtech Systems Support Inc. of Waterloo Canada. Delta Airlines recently employed Navtech to participate in its fuel efficiency program using this flight planning model.

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Table 3-2: **Estimates of Incremental Fuel Consumption, Gallons/Airborne Hour/Pound Increase**

Transport Category (FAR 25)											
Aircraft Category	**Representative Aircraft and Type**	**Engine**	**MTOW**	**Assumed Avg. En Route Time (Minutes)**	**gallons/ hr**	**Weight Increment (lbs)**					
						0-50	**51-100**	**101-200**	**201-300**	**301-400**	**401-500**
Jet: 4 eng wide	B747 - 400	PW4056	870000	600	4018	0.004501	0.004491	0.004487	0.004496	0.004494	0.004493
Jet: 4 eng narrow	DC8 - 62	JT3D-3B	348000	420	2489	0.003525	0.003528	0.003525	0.003526	0.003525	0.003525
Jet:: 3 eng wide	DC10 - 30	CF6-50C2	572000	420	3130	0.005861	0.005868	0.005867	0.005867	0.005871	0.005870
Jet: 3 eng narrow	B727 - 200	JT8D-217C	209500	180	1844	0.010079	0.010088	0.010089	0.010090	0.010091	0.010093
Jet: 2 eng wide	B767-332ER	PW4060	412000	360	2001	0.006183	0.006191	0.006193	0.006193	0.006193	0.006194
Jet: 2 eng narrow	B737 - 300	CFM56-3B-2	125500	120	851	0.005789	0.005790	0.005790	0.005792	0.005792	0.005792
Jet: Regional under 40 Seats	LR35 - 35	TFE731-2-2B	18000	120	197	0.005334	0.005337	0.005337	0.005337	0.005338	0.005338
Jet: Regional with 40-59 Seats	CL600 - 2B19	CF34-3A	51000	120	382	0.007900	0.007912	0.007927	0.007940	0.007952	0.007965
Jet: Regional over 59 Seats	F100 - 100	Mk650-15	98000	180	726	0.007900	0.007912	0.007927	0.007940	0.007952	0.007965

Commuter, Normal, Utility, Acrobatic, Category (FAR 23)						
Aircraft Category	**Representative Aircraft for Category and Type**	**Engine**	**MTOW**	**Assumed Avg. En Route Time (Minutes)**	**gallons/hr**	**Weight Increment (lbs) 0-100**
Turbo Prop (20 or more Seats)	METRO	TPE331	14500	180	72	0.003488
Small Turbo Prop (Under 20 Seats)	SF340	CT7-5A2	28000	60	129	0.001006
Multi-Engine Piston	Beech		5200	60	25	0.003046
Single Engine Piston	Cessna		1700	60	12	0.005238

FAR and Aircraft Category	**Representative Aircraft for Category**	**Assumed Avg. En Route Time (Minutes)**	**0-100**
FAR 27: Rotorcraft > 6000 lbs	(B212)	60	0.059701
FAR 29: Rosecraft < 6000 lbs	(MBB 125)	60	0.028124

The model estimates base fuel burn for a particular aircraft type and a user-specified average takeoff weight and en route time. It then calculates the fuel consumption based on a specified increase in takeoff weight. The difference in the two calculations is the incremental consumption resulting from the additional weight. The flight planning model was used to develop estimates of incremental fuel consumption in this report for the FAR 25 category and large turbo jet category under FAR 23.

For smaller aircraft in the FAR 23 category and rotorcraft in the FAR 27 and 29 categories the flight planning model could not be used due to data limitations. Therefore, flight plans were run manually using manufacturer specifications. The methodology for the manual calculations is identical to the computer program that runs the flight planning model.

In the case of rotorcraft (FAR 27 and 29), further assumptions were required in order to determine the incremental fuel consumption. Fuel burn analysis for these categories is complicated by the fact that flight plans are rarely consistent for rotorcraft in terms of flight times, altitudes, and maximum speed. The fuel burn analysis assumes cruising altitudes of 6000 feet for the B212 rotorcraft and 4000 feet for the MBB 125 rotorcraft and corresponding maximum speeds. These are representative cruising altitudes for rotorcraft in a commercial environment. En route time for both rotorcraft is assumed to be one hour.

Rotorcraft incremental fuel consumption is significantly higher than that for other aircraft. Rotorcraft use different flight paths requiring greater force and fuel consumption to reach cruising altitude. Additionally, fuel burn per hour varies considerably from other aircraft due to changes in cruising altitude and the inconsistency in rotorcraft flight patterns.

Average takeoff weights were obtained from, Flight International, *Commercial Aircraft of the World*, (September 1991). This publication provides average takeoff weight information for a broad range of aircraft in the transport category (FAR 25).

A Transport Canada unpublished study estimated the average weight of each aircraft type departing from Pearson International Airport in Toronto. This study provided verification of average takeoff weights assumed for representative aircraft in FAR 25 and 23. Additional takeoff weight information for the FAR 23 ,27 and 29 aircraft categories was obtained directly from manufacturer flight planning records.

Average en route times for the representative aircraft were calculated using the *Official Airline Guide*, (OAG), which gives flight schedule information by aircraft type. This source provides average en route times for aircraft in the FAR 25 category. Information on hours flown by aircraft type and number of landings was obtained from: Federal Aviation Administration, *General Aviation Activity & Avionics Survey*, (1991). This information was used to calculate average en route time for the FAR 23, 27 and 29 categories. Federal Aviation Administration, *Census U.S. Civil Aircraft* (1991), provided similar information for aircraft in the FAR 25 category which was used to verify the OAG data.

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The above sources provided the basis for selecting representative aircraft based on average takeoff weight, frequency of use and base fuel consumption characteristics. In addition, the Flight International and Transport Canada studies verified the total fuel consumption figures cited in the selection tables. Both studies estimated fuel consumption on an hourly basis using aircraft manufacturer specifications.

3.3 Summary Estimates ~~Per~~ by (?) Category

This section presents a table that summarizes the data shown on Table 3-2 for FAR categories and User Categories. The coefficients are determined based on an average of the operational categories listed above.

Table 3-3: Summary Table for Fuel Consumption Estimation

Category	Assumed Avg. En Route Time (Minutes)	gallons/ hr	0-50	51-100	101-200	201-300	301-400	401-500
User Category								
Scheduled Commercial	280	1738	0.00576	0.00584	0.00584	0.00580	0.00580	0.00579
Air Carrier without commuters	350	2389	0.00602	0.00602	0.00602	0.00603	0.00602	0.00601
Commuter Only	140	435	0.00523	0.00547	0.00546	0.00536	0.00536	0.00536
General Aviation and Air Taxi	90	59.5	0.003194465					
FAR Category								
FAR 25	280	1738	0.00576	0.00584	0.00584	0.00580	0.00580	0.00579
FAR 23	90	59.5	0.003194465					
FAR 27	60	N/A	0.059701					
FAR 29	60	N/A	0.028124					

4. FUTURE OUTLOOK

A related and an increasingly important issue is the fuel consumption level due to congestion and queuing in the airport. The analysis of this topic can be critical to commercial carrier because they are highly sensitive to fuel consumption and they mainly travel during peak-hours when airports are highly congested. We recommend that future analysis of fuel burn should include this issue to better assess the aircraft operating costs due to airport congestion.

The information contained in this report is based on 1996 data. Aircraft mix, fuel efficiency and takeoff weights will change over time. As a result, the incremental fuel consumption tables will need to be continuously updated. For the transport category, FAR 25, updates will be required more frequently than for other aircraft categories. This category includes the air carriers without commuters and commuter only aircraft which are more sensitive to the cost of fuel burn and therefore, more likely to use the most advanced technologies to minimize fuel burn.

For FAR 25, we recommend that the fleet mix and corresponding fuel burn estimates be reviewed every two years. In the event that significant changes occur, the flight planning model should re-estimate the incremental fuel burn for inclusion in the look-up tables. For the remaining categories, FAR 23, 27 and 29, we recommend that the estimates be reviewed every four years.

APPENDIX 1 -REVIEW OF EXISTING FUEL CONSUMPTION MODELS

Introduction

This appendix briefly reviews fuel consumption models in the Federal Aviation Administration report, *Economic Values for Evaluation of Federal Aviation Administration Investment and Regulatory Programs*,(October 1989).[2]

The review concentrates on the theoretical foundations and statistical techniques of the models in the report. The accuracy of results, suitability of aircraft segmentation, and reliability of data sources are also reviewed.

The FAA report is based on fuel burn estimation models developed by Gellman Research Associates (GRA). The models are broken into three segments; Air Carrier, Commuter and General Aviation to estimate the effects of weight increases on fuel consumption. The three model segments differ in terms of functional form, accuracy of results and data sources used.

Theoretical Foundations of Current Fuel Consumption Models

The functional forms used in the GRA models do not adequately consider all of the variables that determine fuel consumption. Furthermore, inconsistencies among the models compromise the accuracy of the results. The following discussion points to the major problems associated with the theoretical foundations of the models.

The existing fuel consumption models assume that the effect of a weight increase on fuel burn is equivalent during all stages of an aircraft flight. The fuel consumption estimate is calculated as an average fuel consumption over the entire flight. However, fuel consumption varies widely during taxi, takeoff, ascent, cruise, descent and landing. As well, flying altitude and maximum aircraft speed are not adequately considered in the models.

The variation of fuel consumption over the duration of a flight is also dependent on the size, engine configuration and flight length of a particular aircraft. The theoretical foundations of the models do not capture the specific characteristics of an aircraft type.

For example, The General Aviation model breaks down aircraft into 4 components: single engine, multi-engine, turboprop and turbojet. The turbojet component consists of a wide variety of plane types including large B747, wide body 4 engine jets and small independently owned corporate jets such as CL600. Including large and small aircraft in the same model produces inaccurate results. The flight pattern for a B747 with an average takeoff weight of 800,000 pounds varies significantly from a CL600 corporate jet with an average takeoff weight of 42,000 pounds (See Table 3.1 for fuel burn estimates). As well, the three models contain many similar types of aircraft in terms of engine configuration and takeoff weight.

[2] Fuel consumption estimates are included in Section 7 of the report, "Models to Estimate Weight Penalties Due to Regulatory Changes."

Statistical Estimation Techniques Used in Current Fuel Consumption Models

Statistical techniques used in the current fuel consumption models do not produce consistently accurate results. The problems arise because the models attempt to predict fuel consumption across a diverse range of aircraft. Gallons per block hour is used as the metric for fuel consumption. This metric is suitable for aircraft that have high airborne to block hour ratios but is not suited for aircraft that regularly fly short flights.

In addition, statistical techniques are not adequately explained. The models employ factor analysis in the Air Carrier Model to correct for collinearity difficulties. However, this analysis is not supported by complete definitions of the factors (i.e., F_1 and F_2). Without these definitions the models are difficult to understand.

Statistical techniques rely on engineering specifications and are limited as a result. Alternative estimation techniques (e.g, Generalized Least Squares) should be considered as a means to correct for collinearity and data deficiencies as factor analysis is not recognized as a means to correct for collinearity. Factor analysis merely imposes restrictions on the model without justification for the factors themselves. In addition, outlier tests that are used in the FAA report need to be clearly defined before results can be validated.

Accuracy of Model Results

Goodness-of-fit tests that indicate forecasting power and accuracy of the estimates show inconsistent results across fuel consumption models and within models. The Aircraft Carrier Model results suggest a log-linear fit of the model for three classes of aircraft -- Narrow Body 3-4 engines, Wide Body 2-3 Engines and Wide Body 4 engines. Additionally, adjusted R^2 results vary widely across aircraft class and do not indicate that the model has good explanatory power. For instance, the model estimating fuel consumption for wide body 4 engine aircraft has an adjusted R^2 of 0.49 which is low compared to other models. Adjusted R^2 results in the Air Carrier Model range from 0.49 to 0.78. The wide interval of values suggests a lack of reliability of the model's results.

Extremely high t-stats for the above classes of aircraft also indicate that the problem of collinearity has not been eliminated. The documentation of the existing fuel consumption models often excludes the t-statistics for the variables and constants used in the model. This information deficiency makes it difficult to determine the extent to which collinearity has been eliminated and the degree of forecasting power of the model.

Comparisons between the fuel consumption results of the GRA models and results of the flight planning model used in this report show that estimates are as much as 50% higher in the GRA models. The flight planning model results are verified by the following source; Flight International, *Commercial Aircraft of the World*, (September 1991) and a Transport Canada unpublished study. Results in the FAA report are not substantiated by industry recognized standards.

Suitability of Aircraft Class Segmentation

The aircraft segmentation used in the existing FAA fuel consumption models does not correspond to Federal Aviation Regulations (FAR). There are 4 major aircraft categories covered under FAA regulation:

- FAR 25, Turbojets
- FAR 23, Commuter, Normal, Utility and Acrobatic aircraft
- FAR 27, Small Rotorcraft (<6,000 lbs)
- FAR 29, Large Rotorcraft (>6,000 lbs).

Existing models do not divide the aircraft in this manner and in many cases two different models with different degrees of accuracy are used for aircraft in one regulatory category. Instead the existing models rely on classifications of aircraft based on whether they are considered air carriers, commuters or general aviation. This breakdown does not allow for accurate estimates of fuel consumption increases caused by regulatory changes within a specific regulation.

The more appropriate approach is to start from the basis of the regulations and assign specific aircraft types to the regulations. This approach is adopted in the current report.

Data Sources

In many cases the 1989 FAA report uses data that has subsequently been updated. The existing fuel consumption models (GELLMAN) use data from: U.S. Department of Transportation, *Aircraft Operating Cost and Performance Report*, 1985; *Business and Commercial Aviation's Aircraft Operating and Performance Data*, (1982-1983); Federal Aviation Administration, *Census of US Civil Aircraft* , 1986; and the Federal Aviation Administration, *Annual Report*, 1987. The first two sources provide information on the aircraft operating characteristics which include manufacturer, weight, climb, cruise and aircraft dimensions. The latter two sources provide information on the number of aircraft in operation and total airborne hours.

The above sources do not include any data available from manufacturers. As well, in all cases more up to date information is now available from the FAA and other sources. Since the FAA report was published there has also been useful information published on the fuel consumption characteristics of several aircraft types. This report includes the most current up to date information and also the benefits from additional data that is now available regarding fuel burn.